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Summary of Investigations of the Use of Modified Turbine Inlet Conditions in a Binary Power Plant

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Abstract

Investigators at the Idaho National Engineering and Environmental Laboratory (INEEL) are developing technologies that will enhance the feasibility of generating electrical power from a hydrothermal resource. One of the concepts investigated is the use of modified inlet conditions in geothermal binary power plant turbines to increase the power generation. An inlet condition of interest allows the expanding vapor to enter the two-phase region, a mode of operation typically avoided because of concern that condensate would form and damage the turbine, degrading performance. INEEL investigators postulated that initially a supersaturated vapor would be supported, and that no turbine damage would occur. This paper summarizes the investigation of these expansions that began with testing of their condensation behavior, and culminated with the incorporation of these expansions into the operation of several commercial binary plant turbines.

Background

During studies conducted on advanced power cycles utilizing mixed hydrocarbon working fluids, INEEL investigators identified a potential increase in performance when the turbine inlet conditions are modified to a allow a metastable expansion through the two-phase region. An example of a cycle using the modified inlet conditions is illustrated in Figure 1. This figure is a temperature-entropy (T-s) plot for an isobutane working fluid that shows the state points for a supercritical cycle, imposed upon the fluid saturation curve. The pumping of the condensate to the heater-vaporizer is the path from point 1 to 2. The path from 2 to 3 represents the heating and vaporization of the working fluid at a supercritical pressure, with point 3 being the turbine inlet. The path from 3 to 4 represents an ideal turbine expansion (isentropic). From point 4 to point 5 the vapor leaving the turbine is desuperheated, and from point 5 to point 1 it is condensed closing the loop.

The amount of superheat shown in Figure 1 at the turbine inlet (point 3) is typical of most commercial plants, although the working fluid is frequently vaporized at subcritical pressures (i.e., a boiling cycle). Plants using isobutane tend to operate above a minimum inlet entropy condition to assure that vapor expanding through the turbine remains "dry" (completely outside of the two-phase region). With the proposed modification to turbine operation, the vapor leaving the heat exchangers is not heated to as high a temperature. From the lower turbine temperature (point 3'), an isentropic expansion to the exhaust pressure passes through the two-phase region and exits the turbine slightly superheated (point 4'). As indicated, turbines in commercial plants avoid this mode of operation because of the concerns that condensate would form (as would be predicted for equilibrium conditions), producing erosion damage and performance losses. However, INEEL investigators postulated that condensate would not necessarily form if the expansions were under metastable conditions rather than true equilibrium.[1] By controlling the inlet conditions to establish the degree to which the expansion entered the two-phase region, operators could prevent condensate formation. This could allow operators to maintain the expanding, supersaturated vapor without causing damage, or degradation to the turbine performance. INEEL studies indicated that the performance of an advanced supercritical cycles using mixed working fluids could be improved by up to 8% by allowing these metastable, supersaturated expansions.[2]

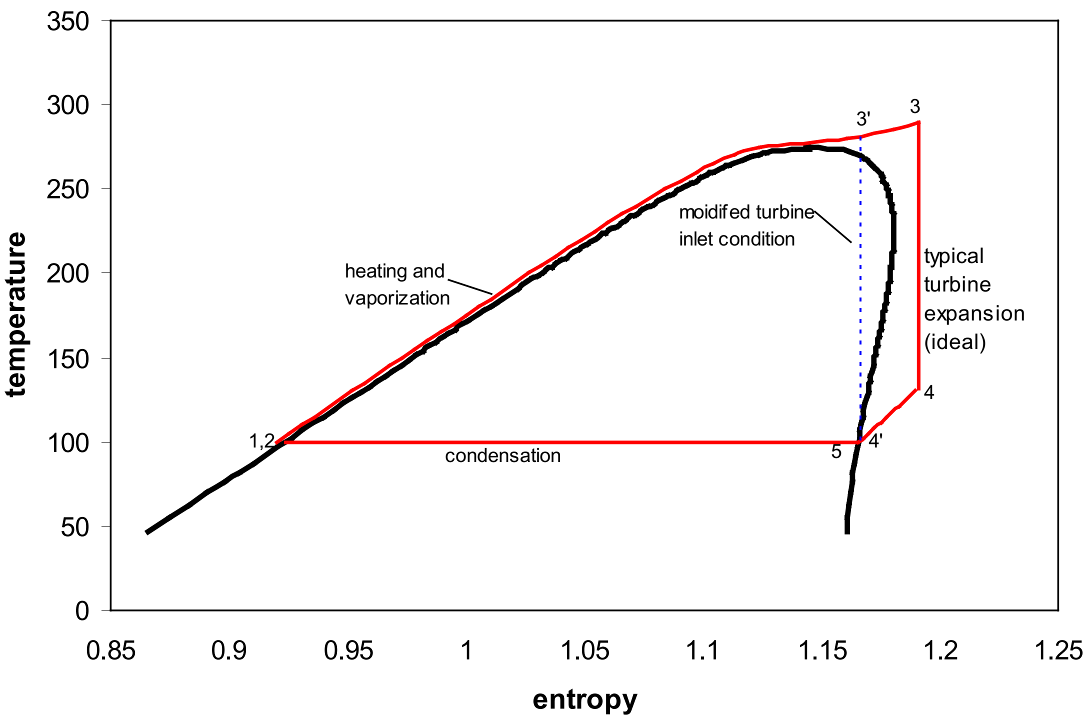

Figure 1: Modified turbine inlet conditions in supercritical cycle using isobutane

Heat Cycle Research Facility Investigations

With the projected benefit of these expansions identified, field investigations were conducted at the Heat Cycle Research Facility (HCRF) located in the East Mesa geothermal field to (a) examine the condensation behavior of these metastable, supersaturated expansions, and (b) determine their affect on turbine performance. The first sequence of testing was conducted using a flow-visualization, expansion nozzle and a system using the scattering of a laser beam to detect the onset of condensation. This nozzle simulated an ideal, isentropic turbine expansion (expansion similar to that occurring in the turbine nozzles). Testing was conducted with pure isobutane and isobutane-hexane mixtures at supercritical inlet pressures. Results indicated the metastable expansions would remain a vapor (supersaturated) until an isentropic expansion from the inlet condition resulted in an equilibrium moisture level of ~5% (the amount of liquid present if the metastable vapor was allowed to reach equilibrium). Using the nozzle results as the basis for defining when condensation should occur, turbines were installed and tested at the HCRF.

The investigation of turbine performance at the HCRF used both an axial-flow, impulse turbine and a radial-inflow, reaction turbine. Testing was conducted at supercritical inlet pressures with isobutane, and isobutane-hexane working fluids. Testing was first accomplished with sufficient superheat at the turbine inlet to assure the resulting expansion remained completely "dry." This established the baseline component performance. With the inlet pressure held constant, the inlet vapor temperature was progressively lowered until a decrease in efficiency was noted. Both turbines operated without any degradation in efficiency at inlet conditions that produced condensate formation in the flow visualization nozzle. As the moisture level increased in the expanding vapor, both turbines reached limits after which their efficiency began to degrade.(4) The impulse turbine did not appear to be affected by the expansions until the actual turbine exhaust was within the two-phase region. The reaction turbine performance began to degrade when its ideal (isentropic) outlet condition was within the two-phase region. Results of the turbine testing at the HCRF are summarized in Figure 2. These tests were limited in duration, and left unanswered the long-term impact of operating with these expansions.

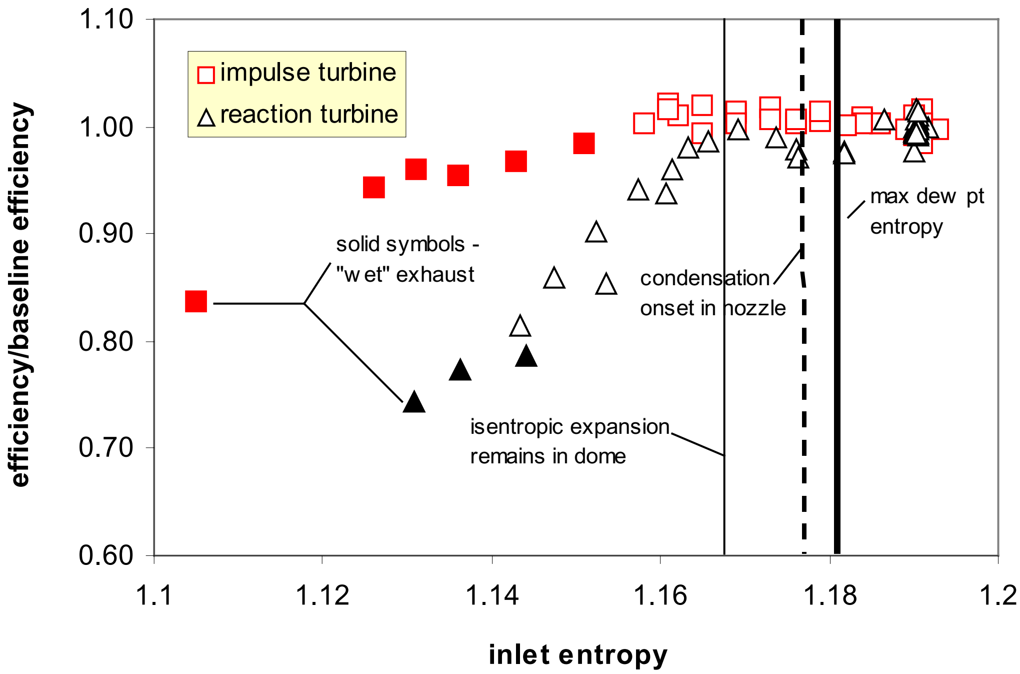

Figure 2: Results of turbine testing at the HCRF showing ratio of observed efficiency to baseline efficiency as a function of the inlet entropy

Testing at Mammoth Pacific's MPI-100 Facility

Following the closure of the HCRF, an agreement was reached with Mammoth Pacific LP that allowed investigators to install a test rotor in Mammoth's MPI-100 facility turbine and operate this turbine with the modified inlet conditions for about 18-months. The turbine is a radial-inflow, reaction turbine designed and built by Rotoflow to generate ~7 MWe (~10,000 hp). The turbine has variable nozzle geometry that provides flexibility in establishing the turbine inlet conditions (flow and pressure). Testing varied from the HCRF investigations in that the Mammoth turbine operates at subcritical pressures. Normally Mammoth operates its turbines with sufficient superheat to assure the fluid is completely vaporized at the turbine inlet (no liquid entertainment) and to avoid expansion into the two-phase region. The level of superheat Mammoth typically maintained is similar (although at a lower pressure) to that depicted by the entropy at the turbine inlet (point 3) in Figure 1.

The extended investigation with the MPI-100 turbine was started in November 1995. Prior to modifying the inlet conditions, the facility was operated at normal inlet conditions to establish the baseline turbine performance with its new rotor. Turbine inlet conditions were then modified through a combination of increased inlet pressure and decreased superheat. Investigators monitored performance of both the turbine and plant with time to identify any degradation that could be attributed to the modified inlet conditions. As the test progressed, the level of superheat was reduced from 2 or 3°F to less than 1°F. The effect of this mode of operation on turbine performance is shown in Figure 3 as a function of air temperature and time. The data indicates that there was little impact on efficiency during the 18-month test period.

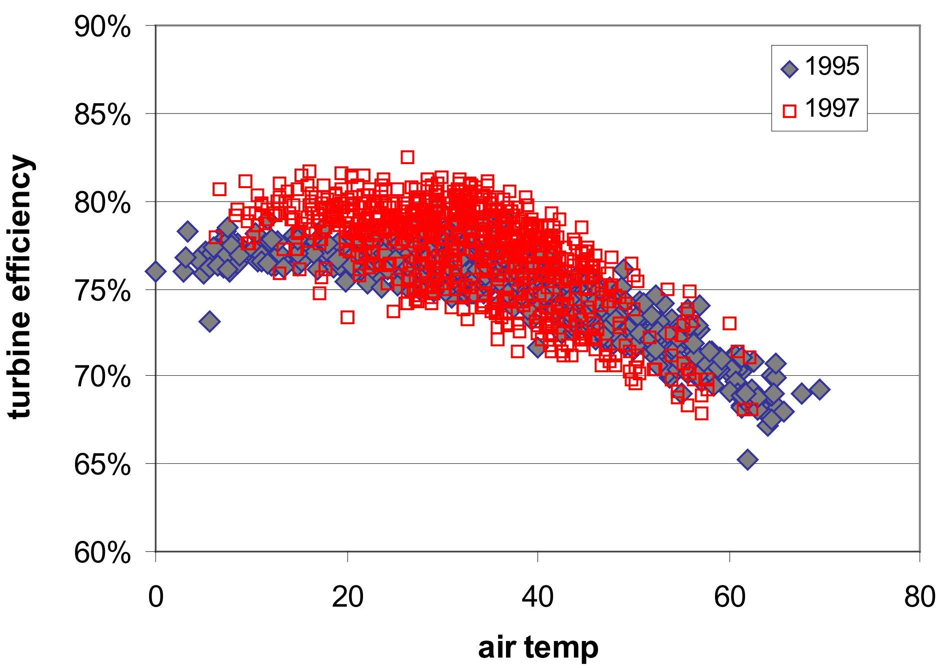

Figure 3: MPI-100 turbine performance as function of air temperature over extended operation with modified inlet conditions

Investigators were also provided with operating data from the MPI-200 plant that continued to operate with typical turbine inlet conditions. This provided a limited comparison of performance between plants operating with and without the modified inlet conditions. (A direct comparison of performance is difficult because neither the brine conditions, nor the baseline performances of the turbines are identical.) The performance advantage the MPI-100 facility had over the MPI-

200 facility during the first 10 months of operation is shown in Figure 4. Over the entire period of time that the MPI-100 turbine was operated with these expansions, the brine effectiveness (power per unit mass of fluid) at this unit was typically 10% to 20% greater than at the MPI-200 unit.

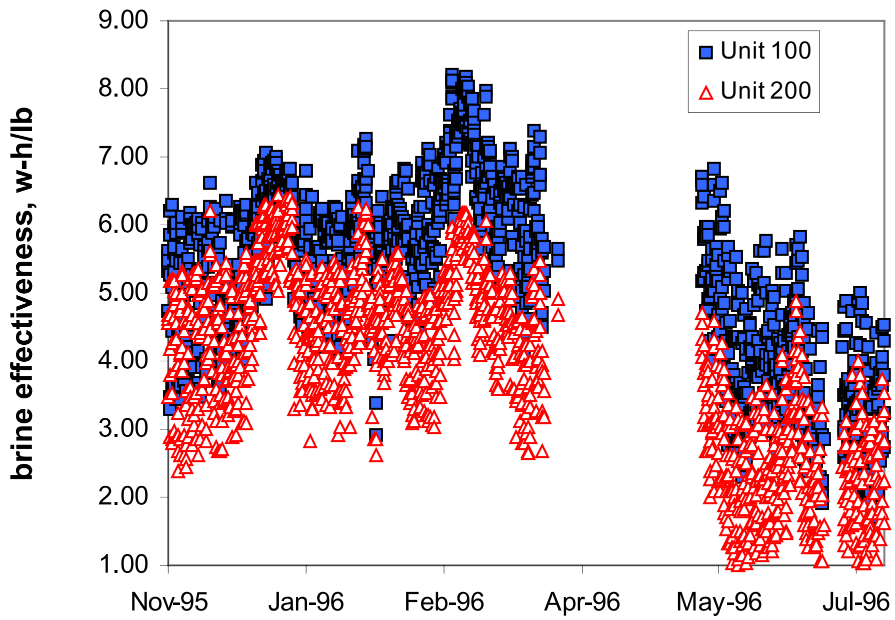

Figure 4: Comparison of MPI-100 and MPI-200 plant performance

In the spring of 1997, the MPI-100 facility was shutdown and the turbine rotor and vanes removed for visual inspection. This inspection revealed some slight abrasive wear on the back side of the turbine rotor blades and on the vane surfaces. Mammoth personnel indicated this wear was typical and did not consider it due to the operation with the modified turbine inlet conditions. (They believed the erosion observed was typical of that caused by solid particulate in the vapor stream.) After completion of the inspection, the rotor was re-installed in the turbine and operation with the modified inlet conditions resumed.

Based upon this inspection, Mammoth modified the turbine inlet conditions at its MPII and PLES plants (also referred to at the G2 and G3 plants) in 1998. Each of these facilities has three turbines, similar in size to the turbine at MPI-100. The inlet conditions were modified by raising inlet pressure and reducing the level of superheat entering the turbine. The modified superheat levels were typically ~3 to 4 ^{o}F at MPII (higher at PLES), which is higher than those used for the MPI-100 turbine. Prior to making this modification, the working fluid flow rate at both facilities was throttled in order to ensure that minimum superheat levels were maintained. Based upon the extended test at the MPI facility, Mammoth felt confident relaxing this minimum requirement and completely opening the flow control valves. However, to increase confidence that the process conditions were being accurately monitored, Mammoth upgraded the instrumentation at the inlet and exhaust of the three turbines at each facility.

The impact of using these expansions on the performance of the MPII plant is shown in Figure 5. In this plot the plant performance (gross power per pound per hour of brine flow) is shown for the period just prior to and just after the turbine inlet conditions were changed. This data indicates an increase in the brine utilization of 0.1 to 0.2 w-hr/lb. This change in operation has minimal impact on the house load (parastics). Thus for a nominal brine flow rate of 2.5 million lb/hr, the change in inlet conditions increased power available for sale by 200 to 500 kW at MPII.

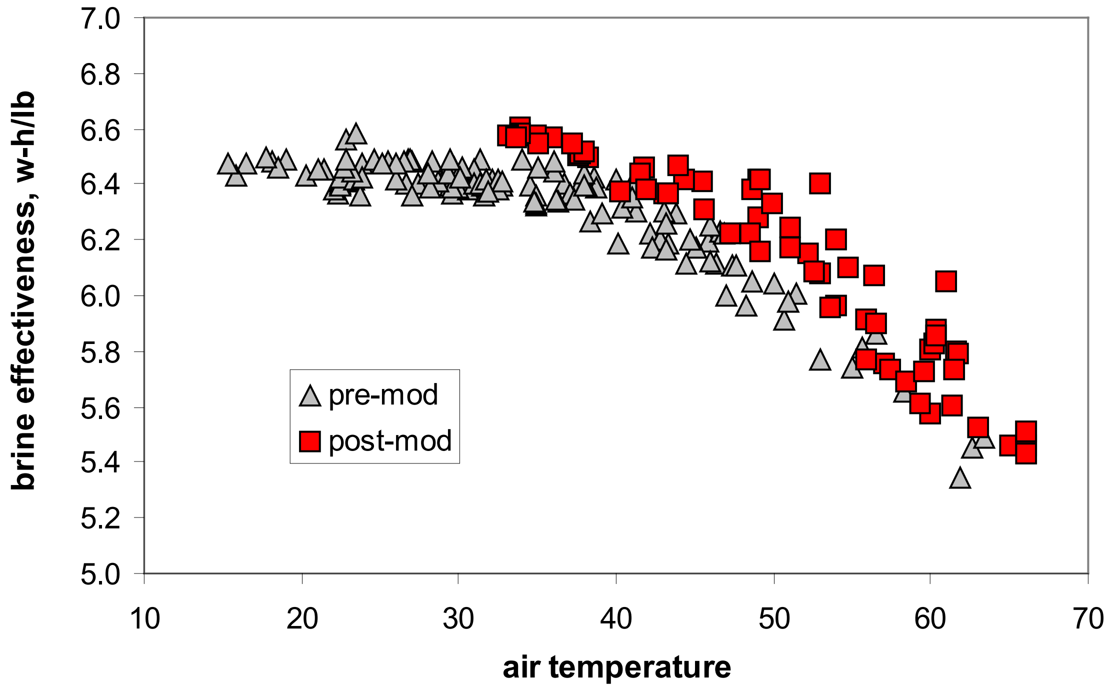

Figure 5: Impact of modified turbine inlet conditions on MPII performance

Mammoth continues to use the modified turbine inlet conditions at the MPI, MPII, and PLES facilities. The degree to which the turbine inlet superheat is lowered in a specific plant varies both from plant to plant, as well as with time. Mammoth uses the modified inlet conditions to provide operational flexibility, allowing power generation to be optimized from all of its generation facilities or from individual plants

Summary and Conclusions

The investigations conducted by the INEEL on the modified turbine inlet conditions have verified that metastable expansions will support a supersaturated vapor, and have provided preliminary limits on the extent to which these expansions can proceed without causing degradation in turbine performance. During the test conducted at Mammoth Pacific's MPI-100 facility, investigators were able to show that these expansions may be applied to subcritical cycles, and that one can reduce the conservatism associated with the levels of superheat typically maintained in these plants. This was accomplished only after taking care to accurately measure and monitor the turbine process conditions.

The Mammoth investigations also showed that these modified inlet conditions can be used to off-set part of the impact of a decline in both geothermal resource temperature and flow. The degree to which this can be accomplished is related to a number of factors that include the design of the plant components, the level to which the resource has declined, and whether the decline has been in flow or temperature.

Acknowledgments

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